Exploring New Physics with Electronic Recoil Data from PandaX-4T Detector

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On behalf of the PandaX Collaboration

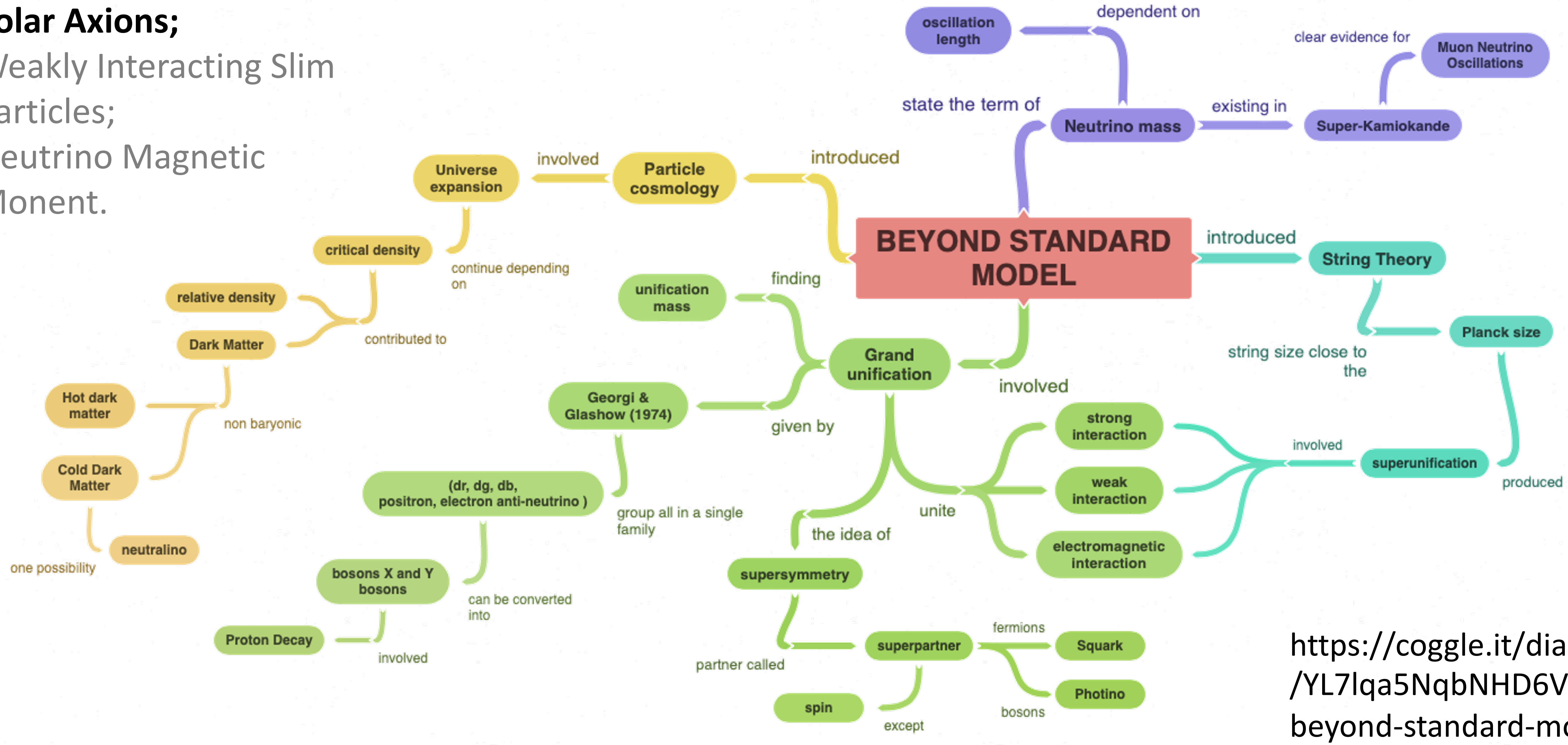
2023.10.21, MEPA 2023, @Hefei, USTC

PANDAX
PARTICLE AND ASTROPHYSICAL XENON TPC

SHANGHAI JIAO TONG UNIVERSITY 1896

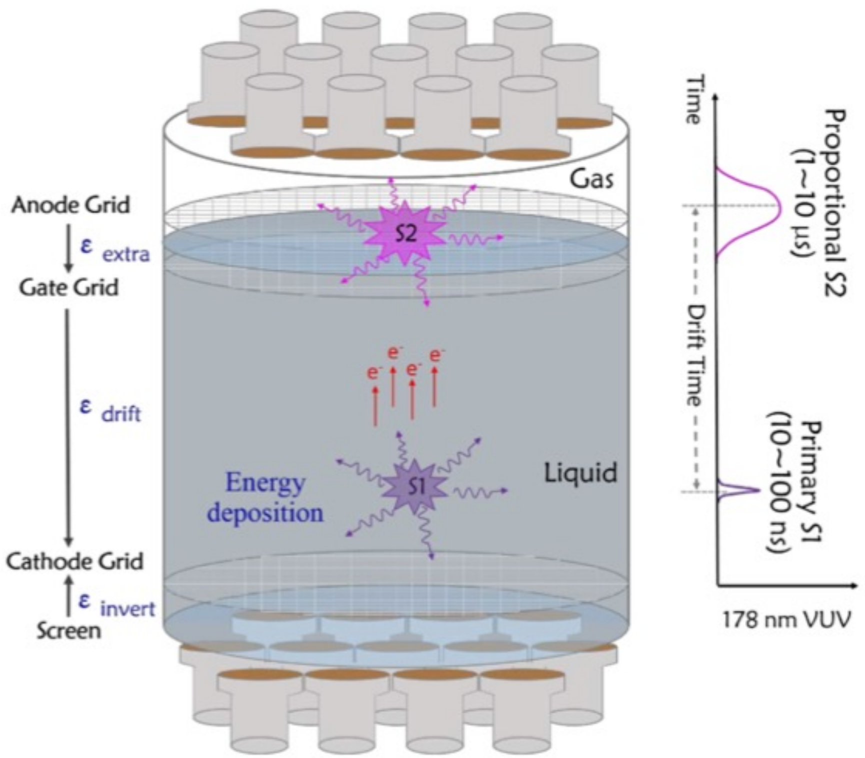
Explosion of New Physics

- **Solar Axions;**
- Weakly Interacting Slim Particles;
- Neutrino Magnetic Monent.



https://coggle.it/diagram/YL7lqa5NqbNHD6VG/t/beyond-standard-model

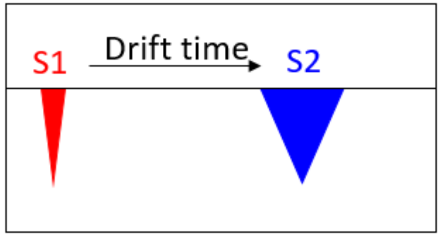
Dual Phase Xenon TPC



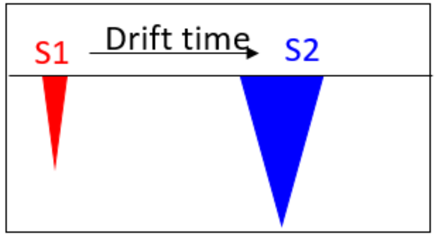
ZEPLIN · XENON · LUX · LZ · PandaX…

1. Large A: large cross section & self-shielding;
2. 3D reconstruction and fiducialization
3. Scalable;
4. Discrimination power
   - WIMPs, ν, n → Nuclear Recoil (NR)
   - Axion, γ, β → Electronic Recoil(ER)

Dark matter: nuclear recoil (NR)

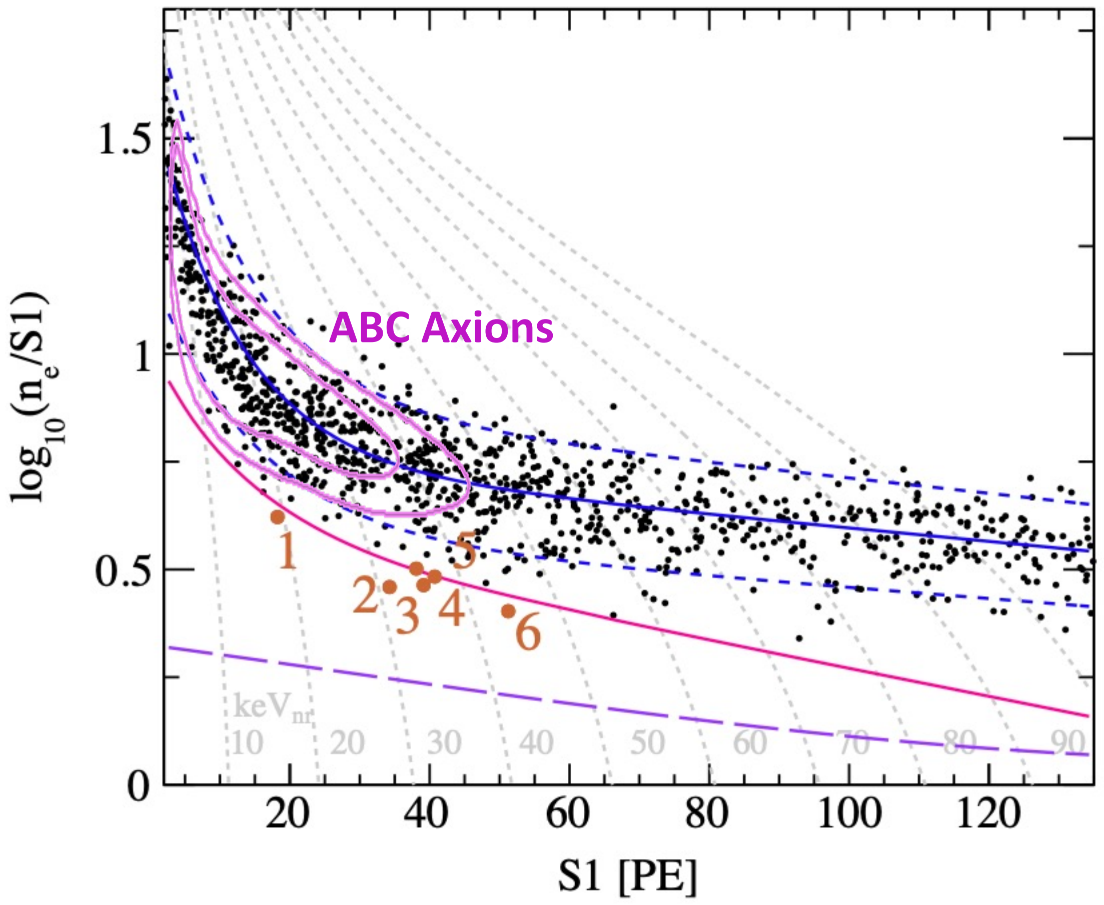


γ background: electron recoil (ER)



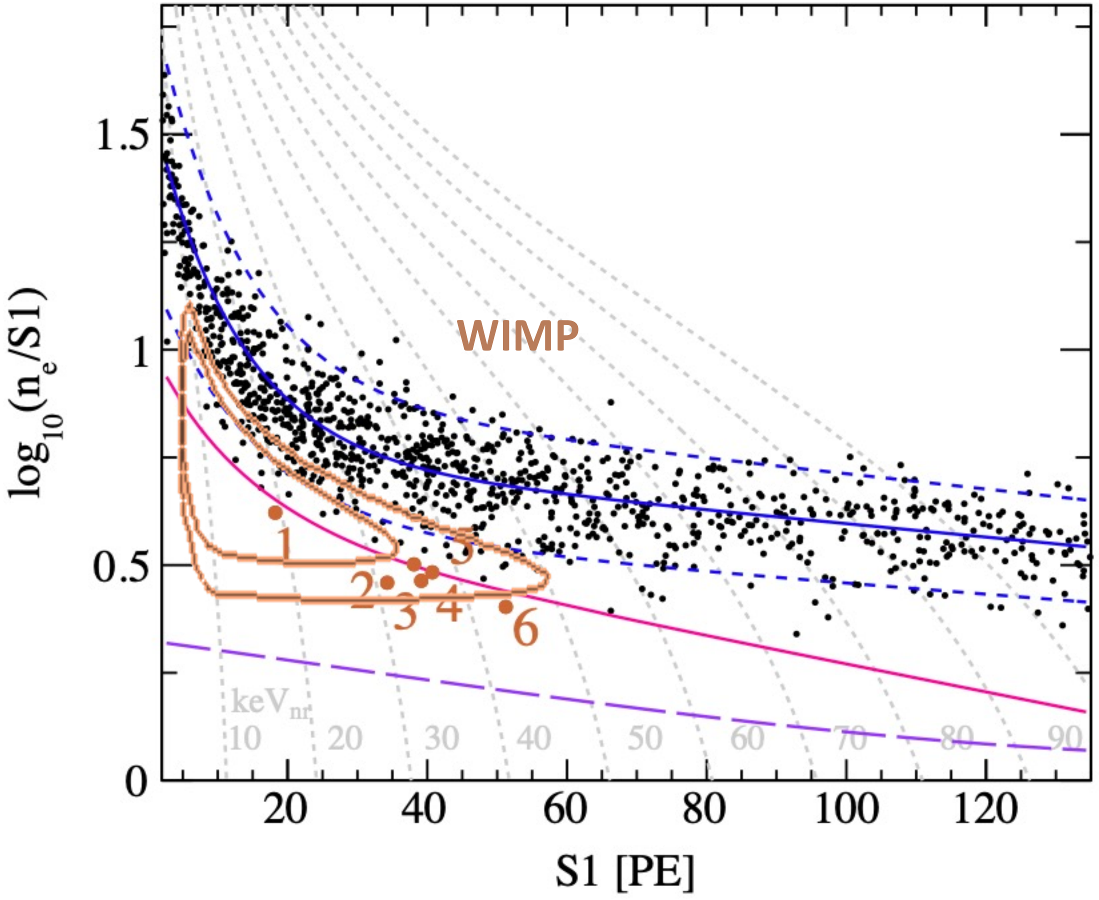
$(S2/S1)_{NR} \ll (S2/S1)_{ER}$

NR Searches V.S. ER Searches



Excess over known ER backgrouds!

Phys. Rev. Lett. 127, 261802



Below NR median **candidates**.

Production Mechanisms of Solar Axion

- Atomic recombination and deexcitation (Axio RD in figure), Bremsstrahlung, and Compton (ABC):

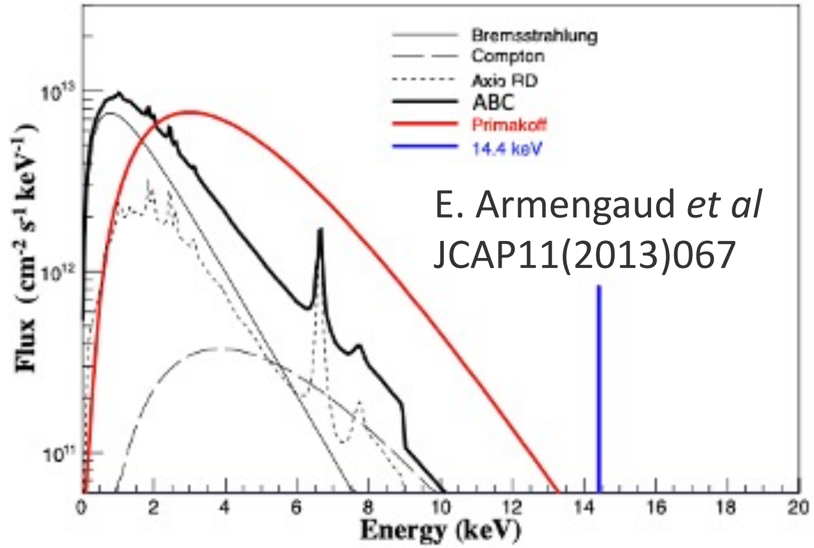
$$\Phi_a^{ABC} \propto g_{ae}^2$$

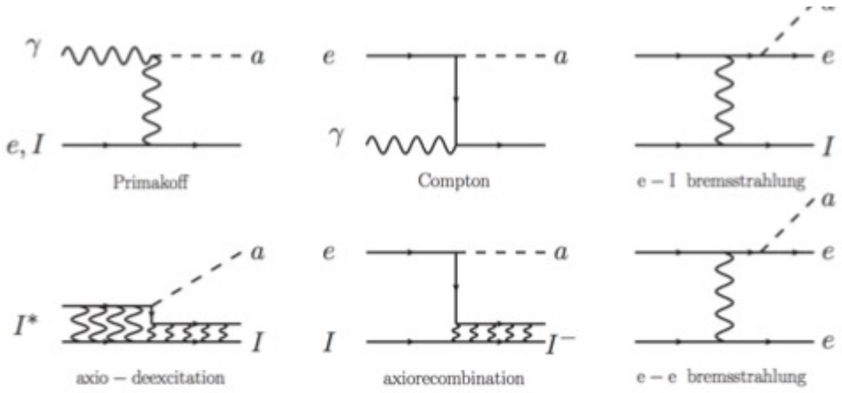
- Primakoff effect:

$$\frac{d\Phi_a^{Prim}}{dE_a} = \left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}}\right)^2 \left(\frac{E_a}{\mathrm{keV}}\right)^{2.481} e^{-E_a/(1.205\ \mathrm{keV})} \times 6\times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1},$$

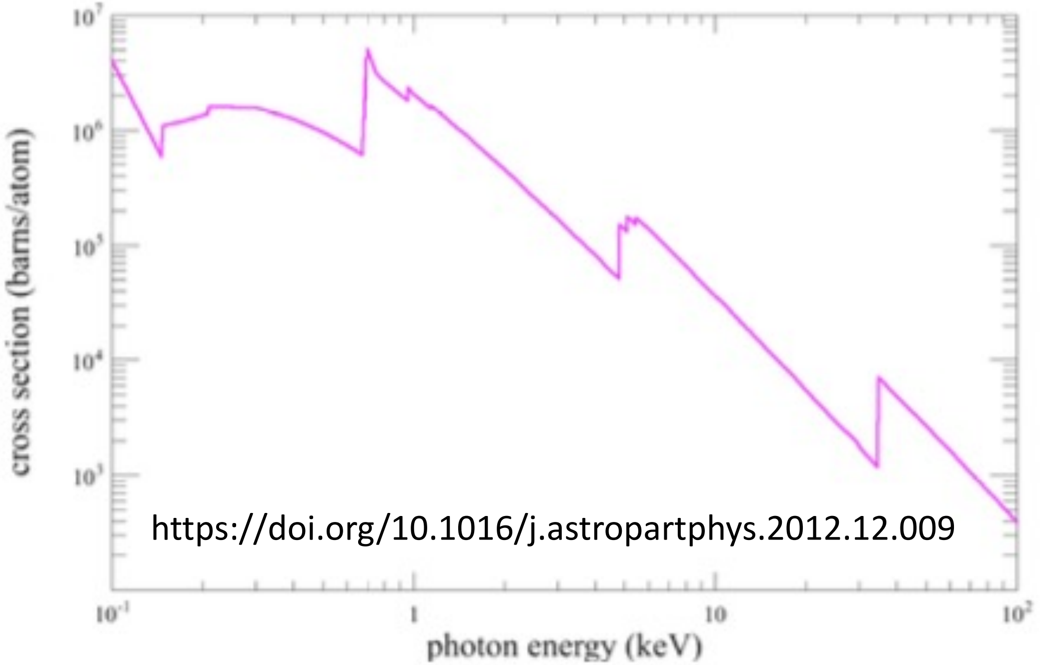
- M1 nuclear transition of ^{57}Fe (14.4 keV):

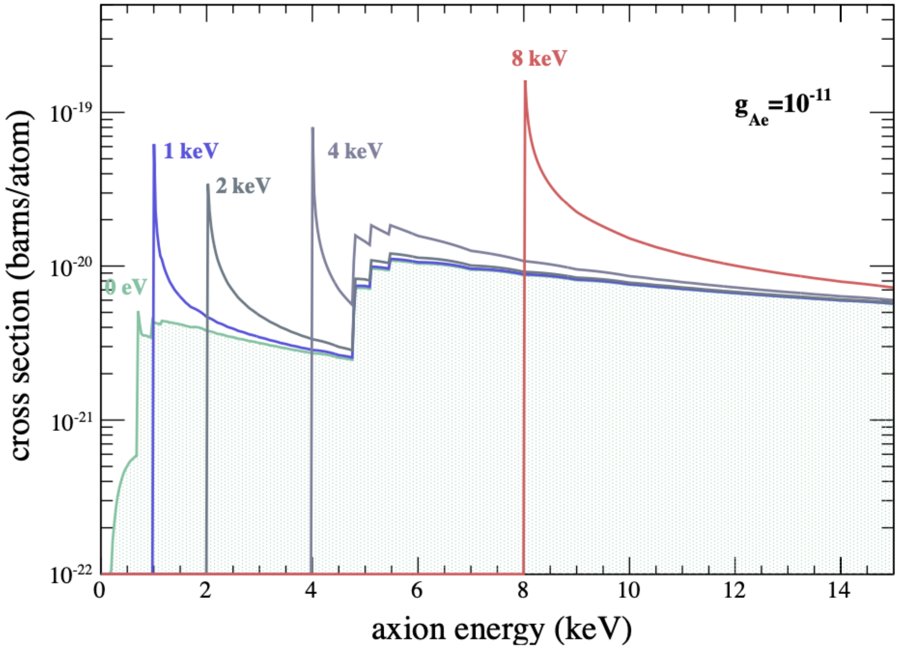
$$\Phi_a^{57\mathrm{Fe}} = \left(\frac{k_a}{k_\gamma}\right)^3 \times 4.56\times 10^{23} (g_{an}^{eff})^2\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$





ER Signals from Axio-electric Effect





The approximate cross section of axio-electric effect is:

$$\sigma_{Ae}(E) = \sigma_{\rm pe}(E)\frac{g_{Ae}^2}{\beta}\frac{3E^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{\frac{2}{3}}}{3}\right)$$

where $g_{Ae} = C_{ae} m_a / f_a$, C_{ae} is model dependent.

Other signals

❑Weakly Interacting Slim Particles (WISPs)

- Axion-like Particles (ALPs)

$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{\mathrm{keV}/c^2}\right) \left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1} \tag{1}$$

- Dark Photons

$$R \simeq \frac{4.7 \times 10^{23}}{A} \kappa^2 \left(\frac{\mathrm{keV}/c^2}{m_{\mathrm{V}}}\right) \left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1} \tag{2}$$

❑Neutrino Magnetic Moment Enhanced Neutrino-electron Scattering

$$\frac{d\sigma_\mu}{dE_{\mathrm{r}}} = \mu_\nu^2 \alpha \left(\frac{1}{E_{\mathrm{r}}} - \frac{1}{E_\nu}\right) \tag{3}$$

Particle and Astrophysical Xenon Experiments

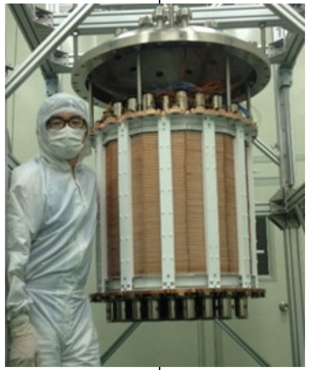
Collaboration formed

2009.3

2014.5-10

PandaX-I, 120 kg xenon operation

PandaX-II, 580 kg xenon operation

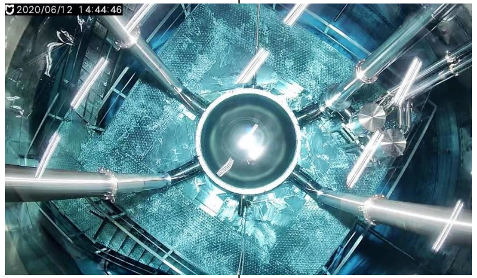


2016.7 -2019.7

2019.8

PandaX-4T, 3.7 ton moved to CJPL-II

PandaX-4T, commissioning run



2020.11-2021.6

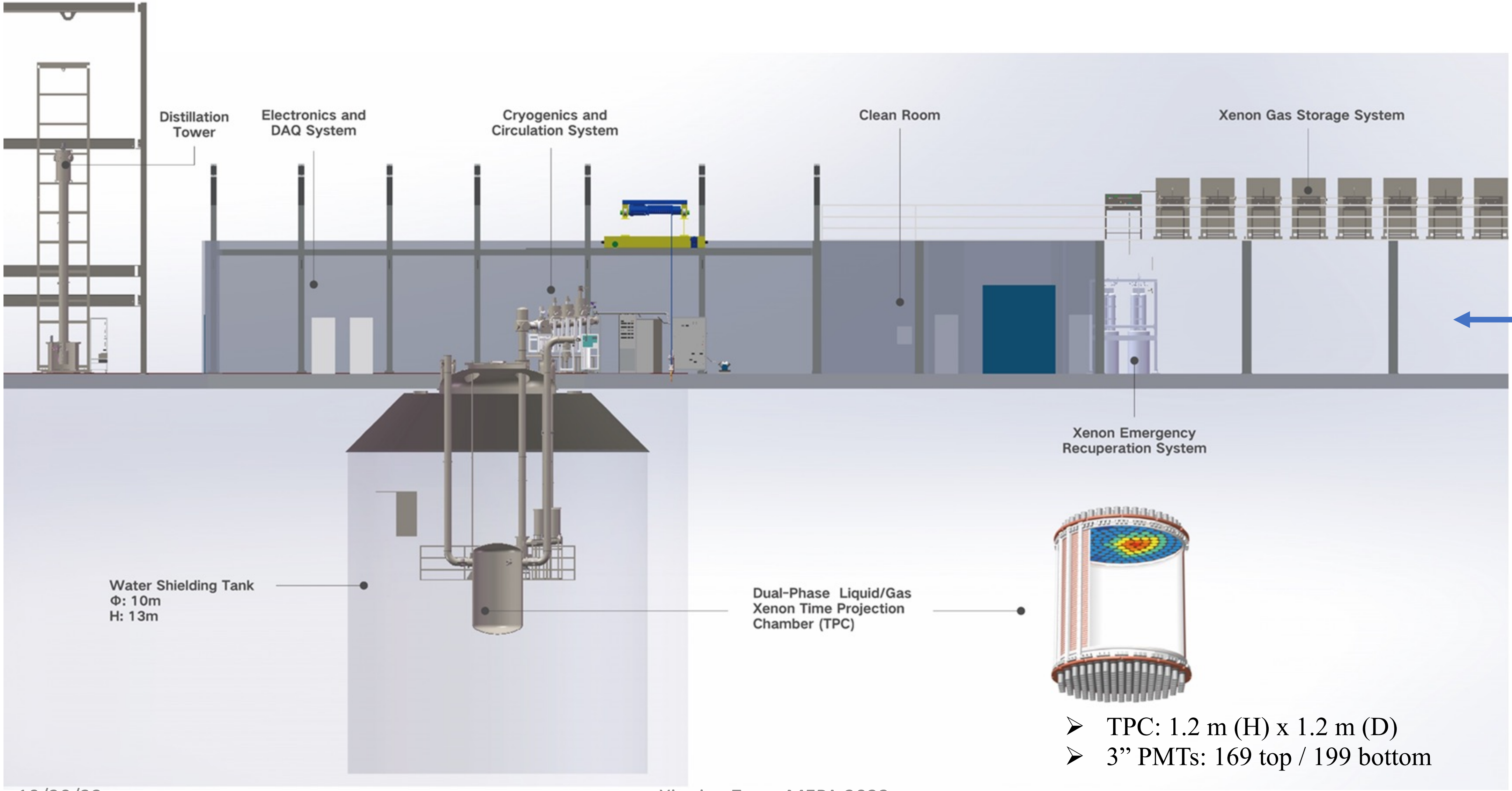
2021.11 – 2022.7

PandaX-4T, physics run

Detector upgrading

2023

PandaX-4T Detector System Layout

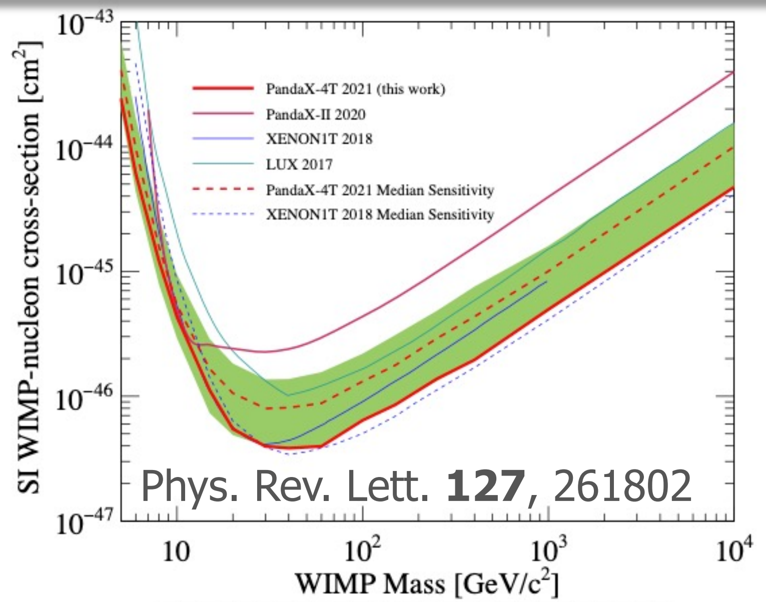


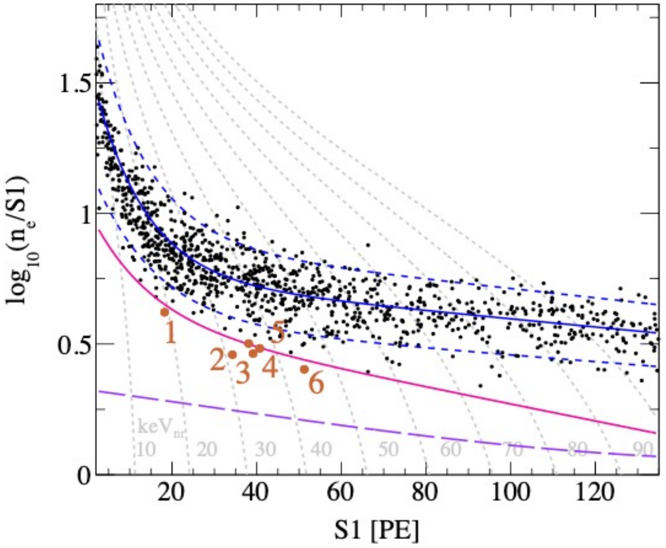
Entry

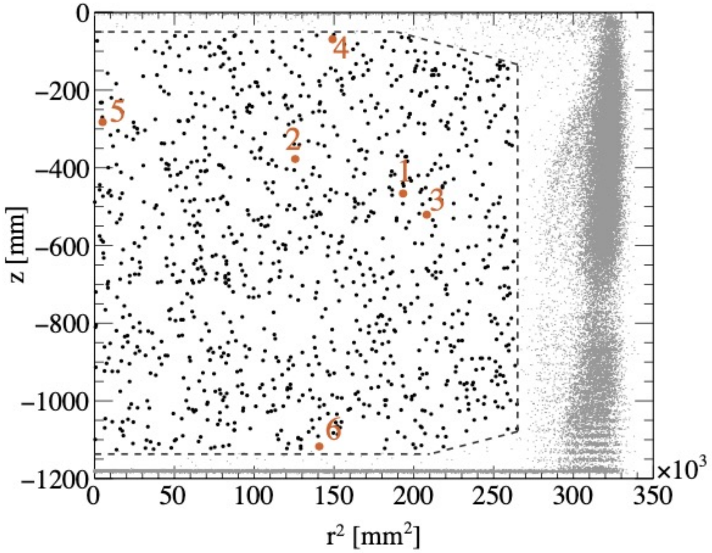
- TPC: 1.2 m (H) x 1.2 m (D)
- 3” PMTs: 169 top / 199 bottom

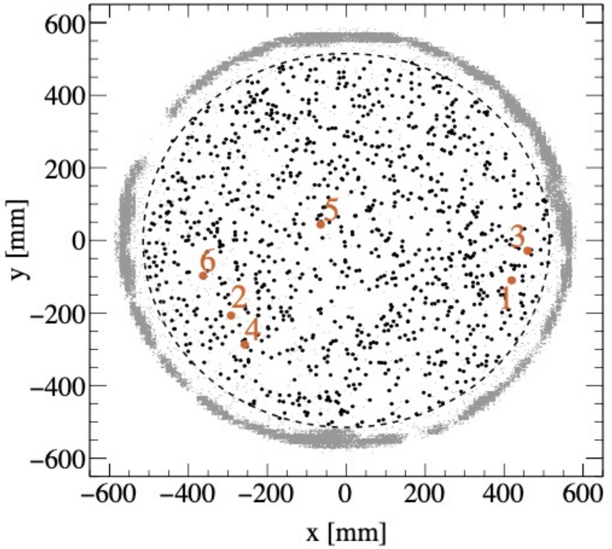
PandaX-4T Commissioning Run (Run 0)

- ❑**Sensitive volume: 3.7 tonne xenon**
- ❑**Commissioning started from Nov/2020 (95 days)**
  - 0.63 tonne-year exposure, 1058 candidates
  - Sensitivity improved from PandaX-II final analysis by 2.9 times (30 GeV/c2);



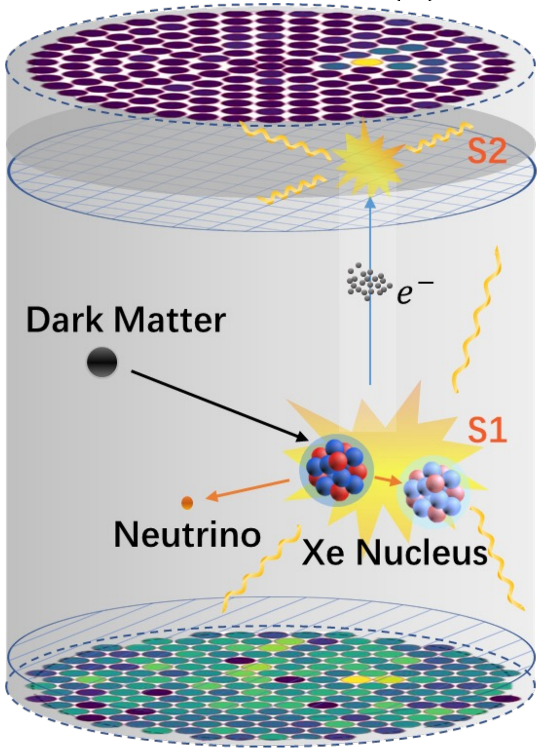




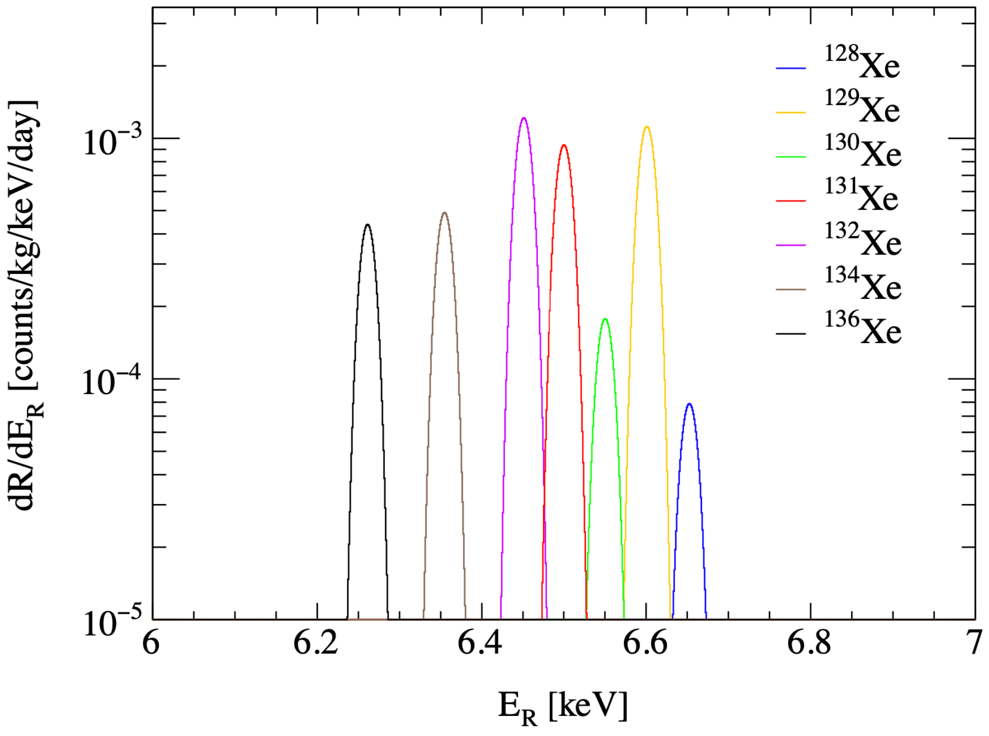


New DM searching channel: $\chi \longrightarrow \nu$

$\chi(\bar{\chi}) + {}^{A}Xe \rightarrow \nu(\bar{\nu}) + {}^{A}Xe$

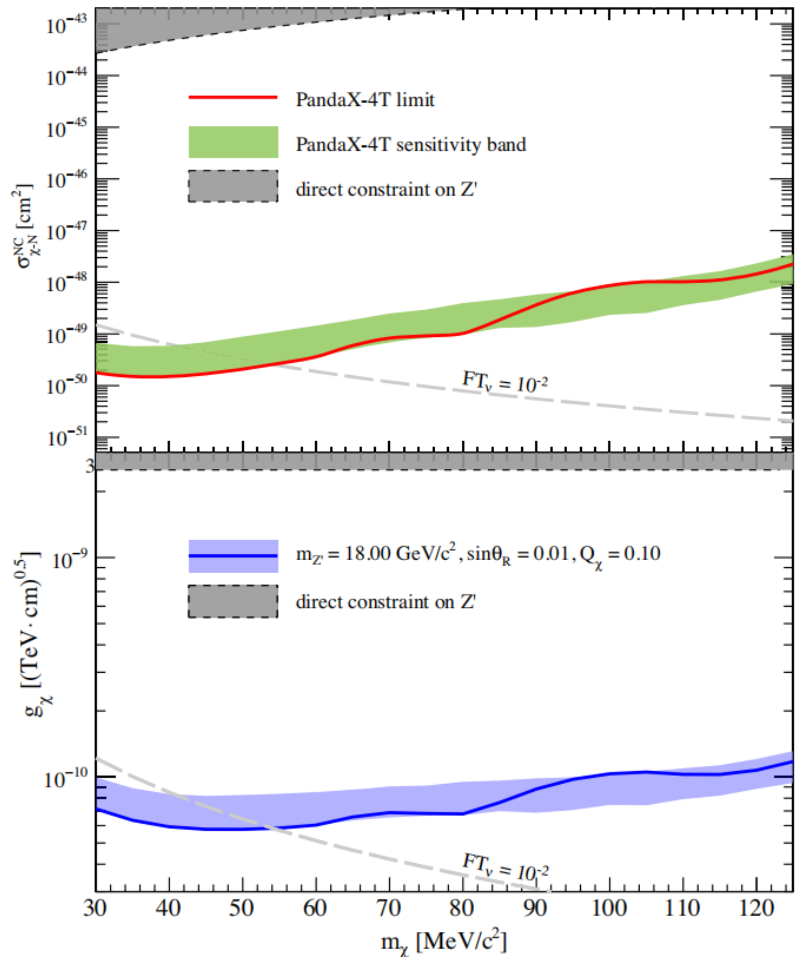


Mono-energetic signal spectrum



- **Elastic scattering v.s. Inelastic scattering (Absorption).**
  - DM being absorbed, with an outgoing neutrino ν
- **Fermionic DM absorption model through neutral current:**
  - Detectable NR signals with higher recoil energy .
  - DM mass range: MeV

New DM searching channel: $\chi \longrightarrow \nu$



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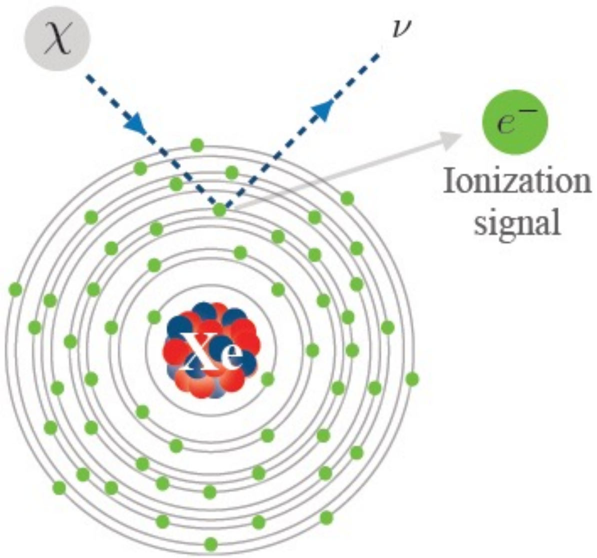
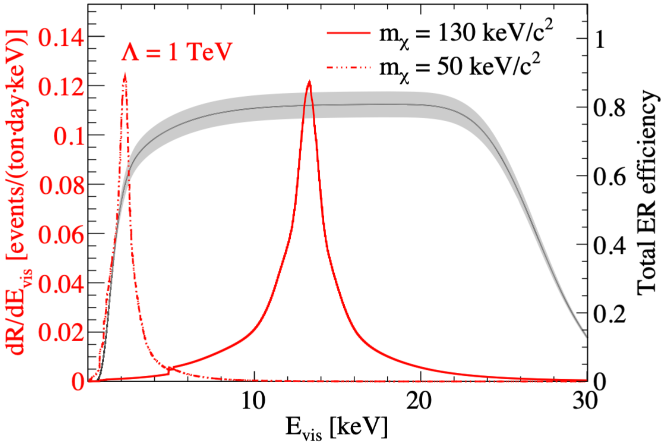
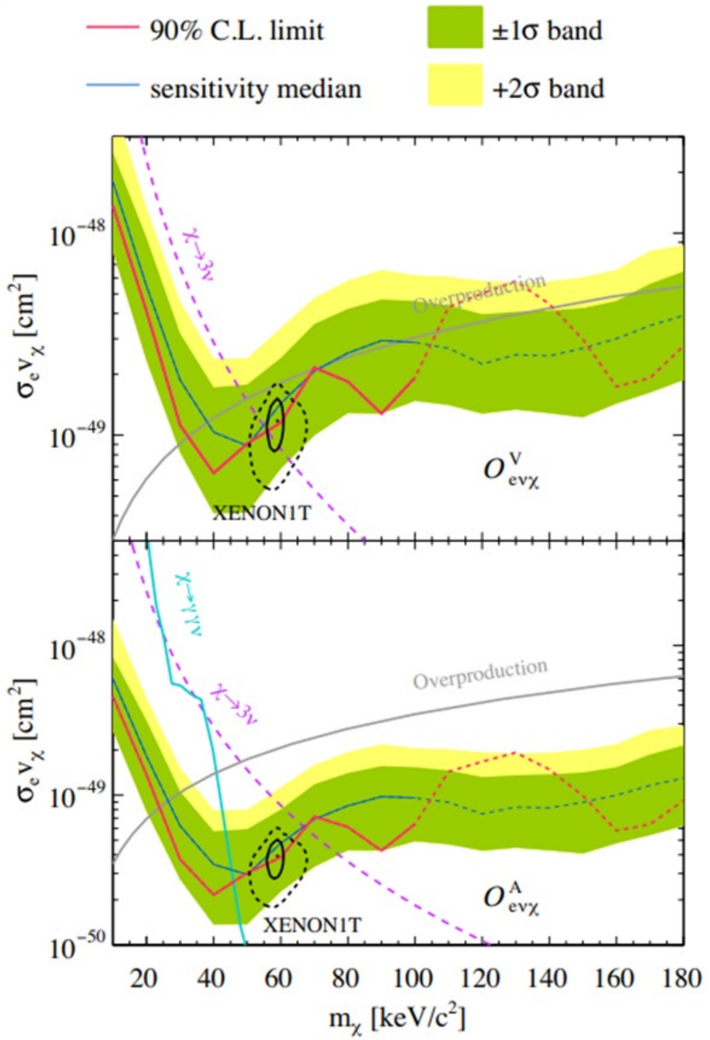
- ❑First search for fermionic dark matter absorption signal in direct detection experiments
- ❑Strongest limit of 1.5 x 10^{-50} cm^2 achieved at 40 MeV/c^2 fermionic DM mass
- ❑Constraints on the coupling g_χ to the order of $10^{-10}(\mathrm{TeV} \cdot \mathrm{cm})^{0.5}$

New DM searching channel: $\chi e \longrightarrow e\nu$







- General fermionic (sterile neutrino-like) dark matter absorption on e⁻;
- Strong sensitivity to vector and axial-vector mediators; Complementary to astrophysical constraints, with much smaller theoretical uncertainties;
- Competitive constraint in 20-55 keV/c^2

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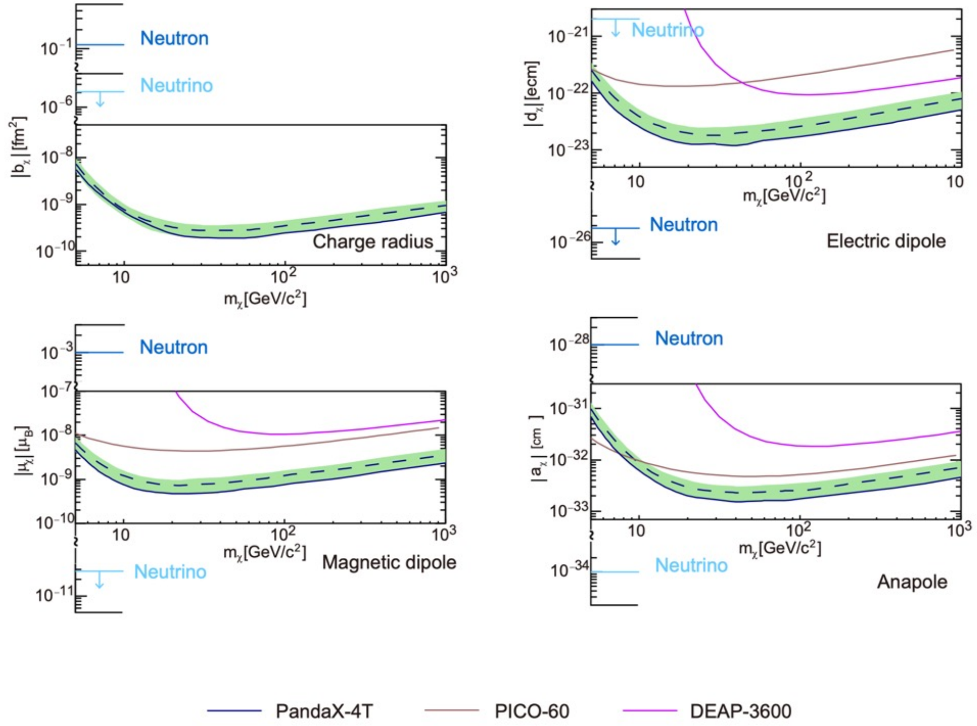
Electro-magnetic Properties of DM

- ❑ **Minute photon-mediated interactions through millicharge or higher-order multipole is still possible;**
- ❑ **Direct search for effective EM interactions: first experimental constraint on DM charge radius;**
  - 4 orders of magnitude smaller than neutrino
- ❑ **Other EM properties.**

Table 1 | Comparison of electromagnetic properties

	Dark matter	Neutrino	Neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$(-2.1,3.3)\times10^{-6}$ [a]	-0.1155 [a]
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ [a]	$(-2\pm8)\times10^{-22}$ [a]
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ [a]	-1×10^{-3} [a]
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ [b]	$<1.8\times10^{-26}$ [a]
Anapole (cm^2)	$<1.6\times10^{-33}$	roughly 10^{-34} [c]	roughly 10^{-28} [d]

[a]Data are taken from the Particle Data Group[33].



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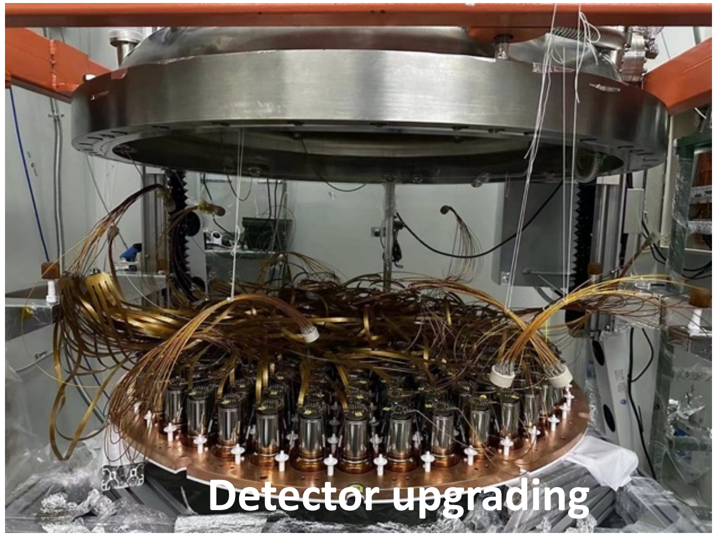
After Run 0

- **Tritium removal**
  - xenon distillation, gas flushing, etc
- **2021/11 – 2022/05: physics run (Run1)**
  - 164 days: ~ 1 tonne-year
- **2022/09 - 2023/10: hall construction**
  - xenon recuperation
  - detector upgraded
- **Expect to resume by the end of 2023**

CJPL-II B2 Hall: under construction

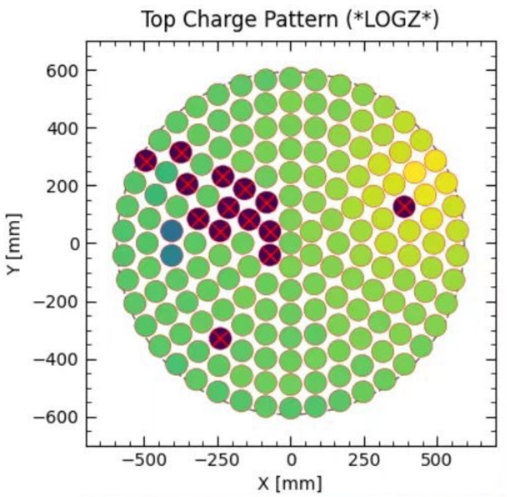


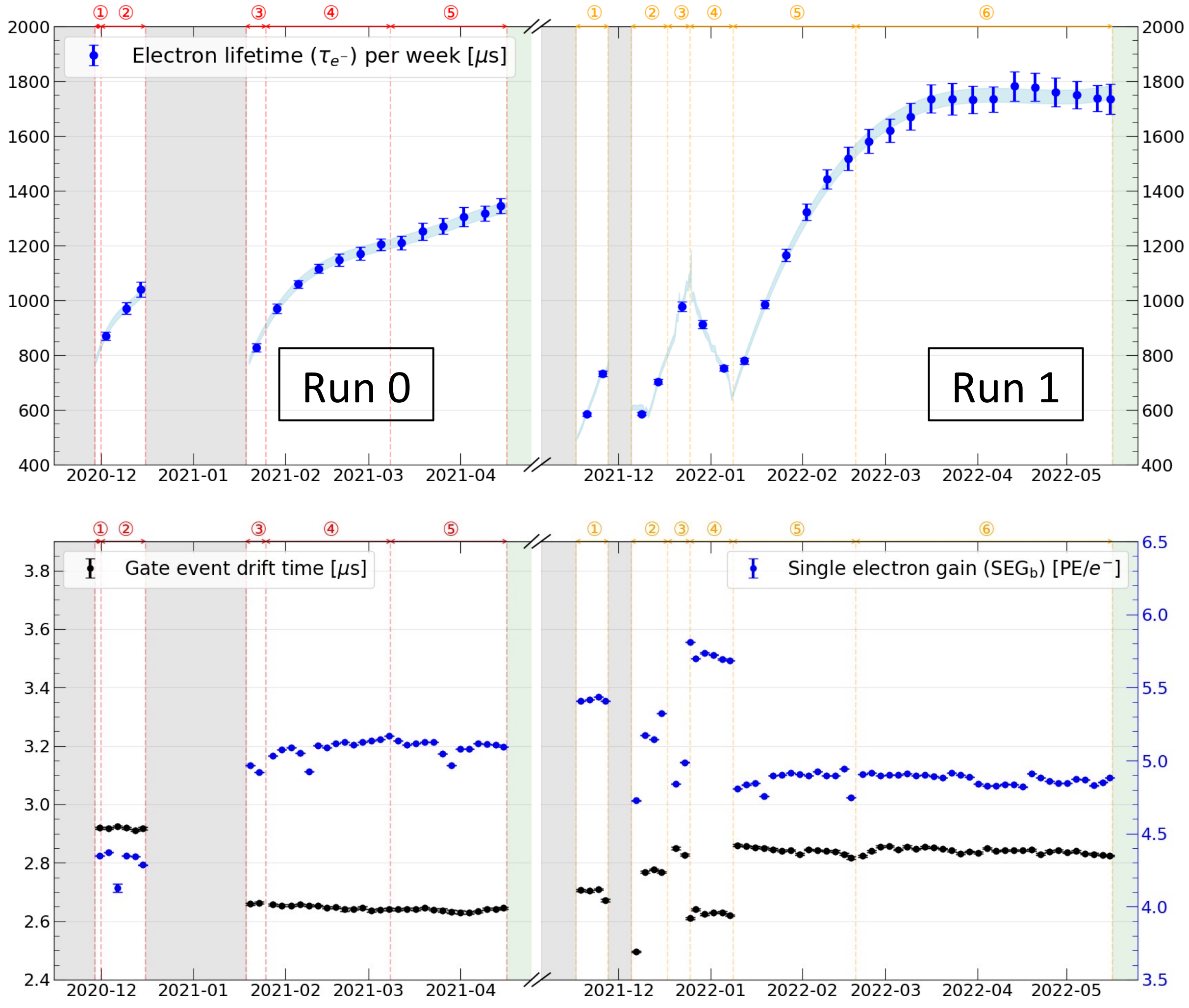
Detector upgrading

Commissioning (Run 0)	Calibration	Distillation	Physics Run (Run 1)	Calibration	Detector Upgrade
2020/11/28 – 2021/04/16	2021/04/17 – 2021/06/09		2021/11/15 – 2022/05/15	2022/05/16 – 2022/07/08	

Data Taking Condition of Run 1

- ❑**Gate -6kV, Cathode -16kV;**
- ❑**Xenon purity monitor: Maximum electron lifetime reaches 1800 us;**
- ❑**Liquid level is monitored through the drift time of gate events and single electron gain (SEG);**
- ❑**Additional 10 top PMTs turn-off.**





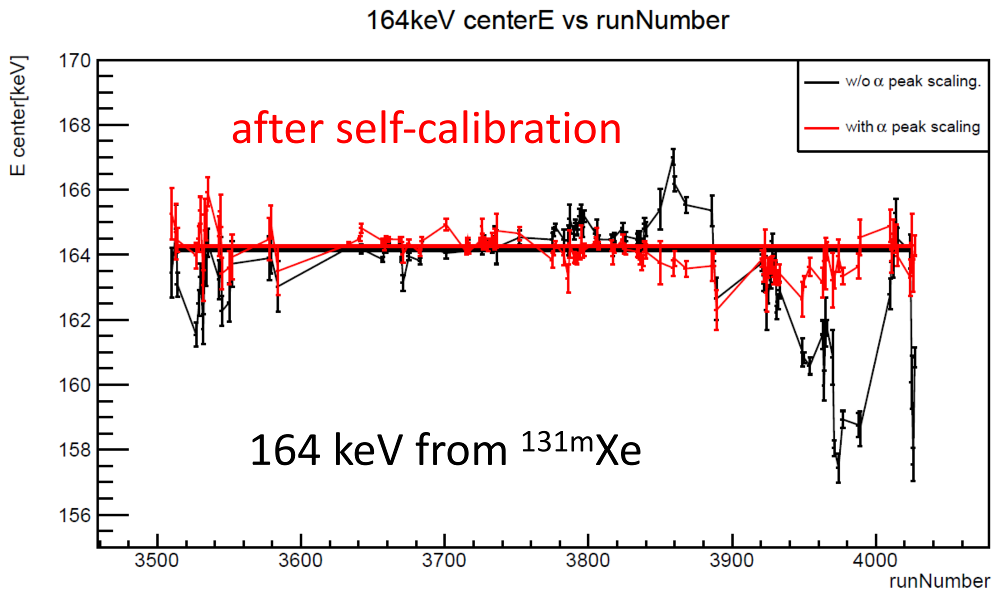
Self-Calibration of PMT Gain and Signal Yield

❑**Degrading of PMTs:**

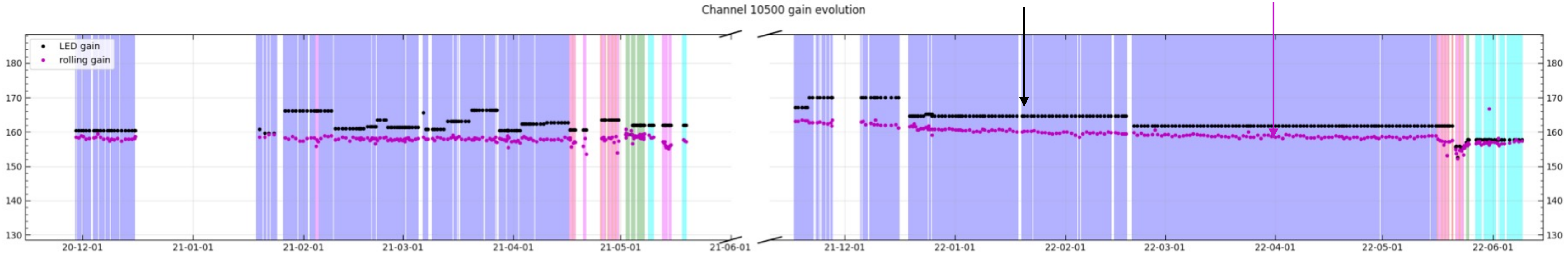
- LED calibration: once a week, not instant monitoring;
- correction factor derived from single hit distribution.

❑**Instability of signal yield: S1 & S2 of monoenergetic peak evolve by time:**

- correction factor derived from S1 and S2 with 5.5MeV alpha events from ^{222}Rn decay;
- likely related to the liquid level.



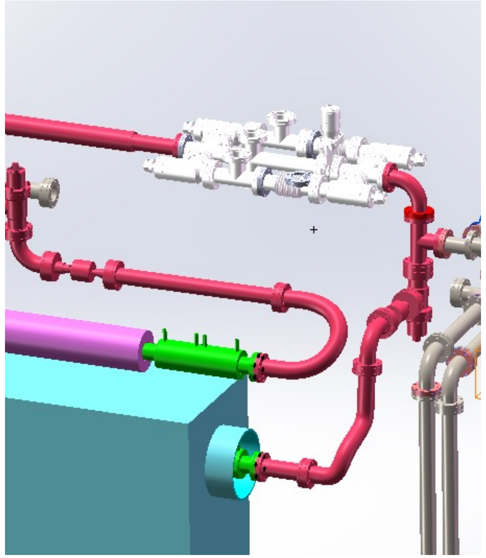
LED calibration vs Self-calibration



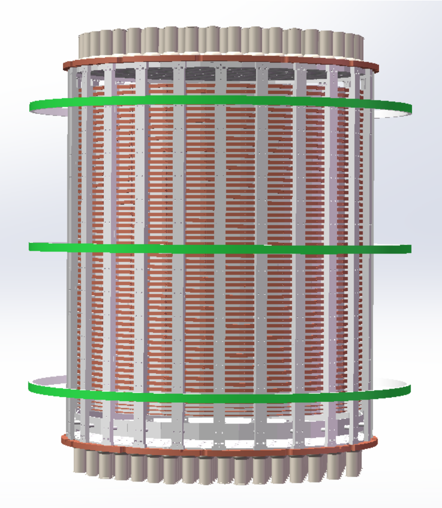
Detector Calibration

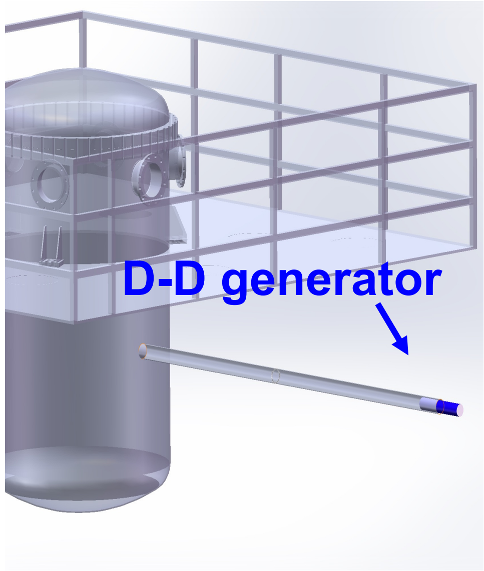
- **Rn, D-D neutron and AmBe neutron for low energy region**

Gaseous source injection panel



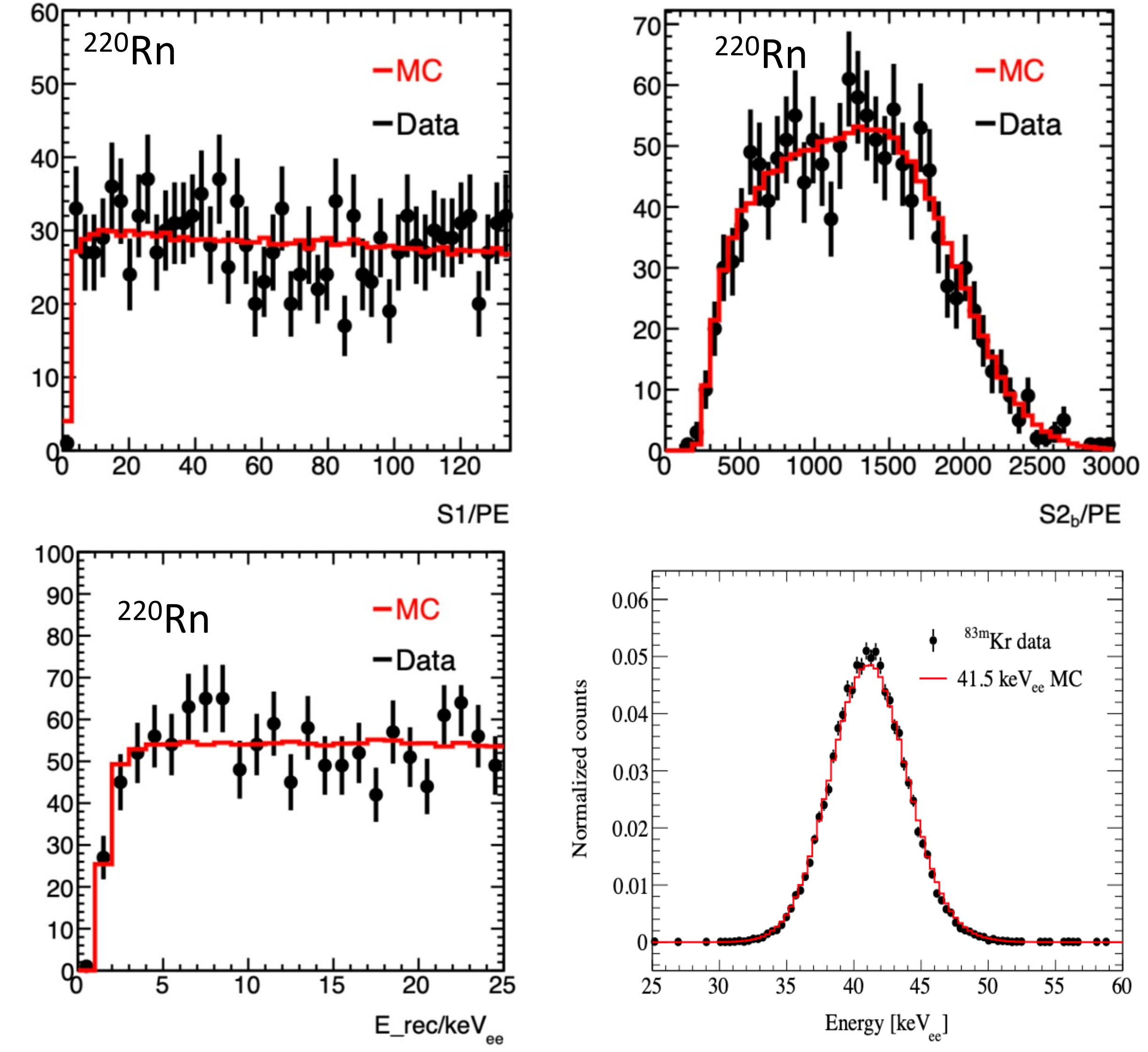
Calibration tubes





Calibration Source	Position
^{83m}Kr/^{220}Rn	Injected from gas panel
^{241}Am-Be、Co、Cs、PuC	Calibration tubes
D-D neutron	Beam pipe

ER Calibration



- The detector response is modelled by NEST (Noble Element Simulation Technique).
- Detector parameters are fit to Rn calibration data using unbinned likelihood fitting with emcee;
- Calibrated NEST fits well with ^{83m}Kr data, both in spectra and resolutions: Energy resolution @ 41.5 keV: **6.8%**

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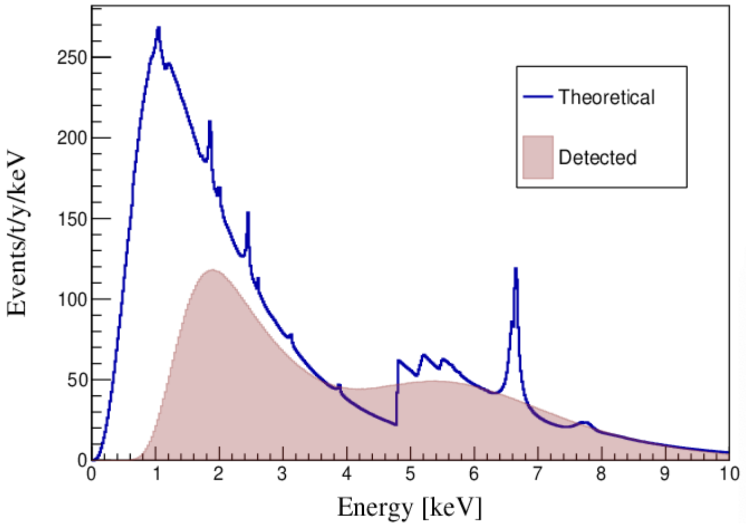
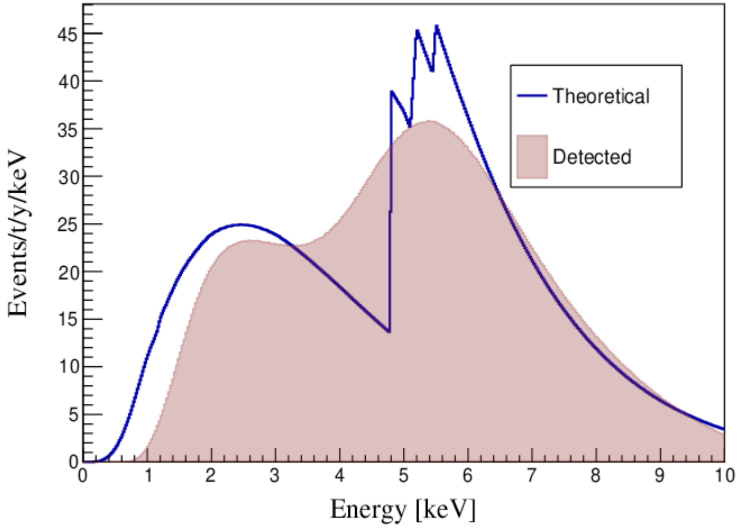
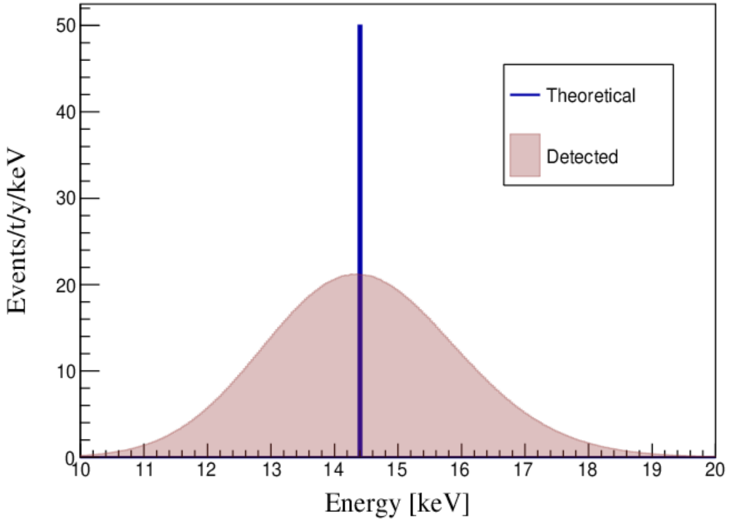
Solar Axion Signals in PandaX-4T



ABC Axion



Primakoff Axion



Fe57 Axion

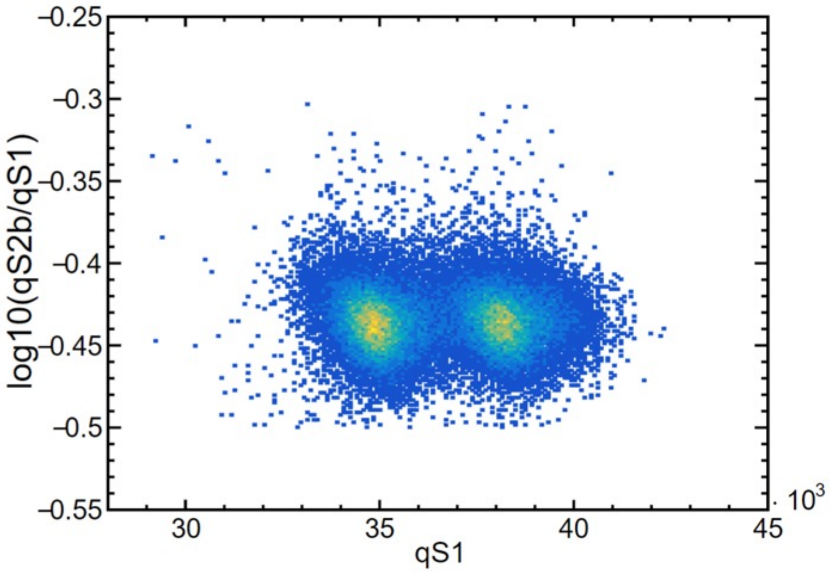
Expected solar axion signals in energy space produced by different mechanisms:

- ABC process: $g_{Ae} = 5\times10^{-12}$;
- Primakoff effect: $g_{A\gamma} = 2\times10^{-10}$
- ^{57}Fe nuclear transition: $g_{An}^{eff} = 1\times10^{-6}$

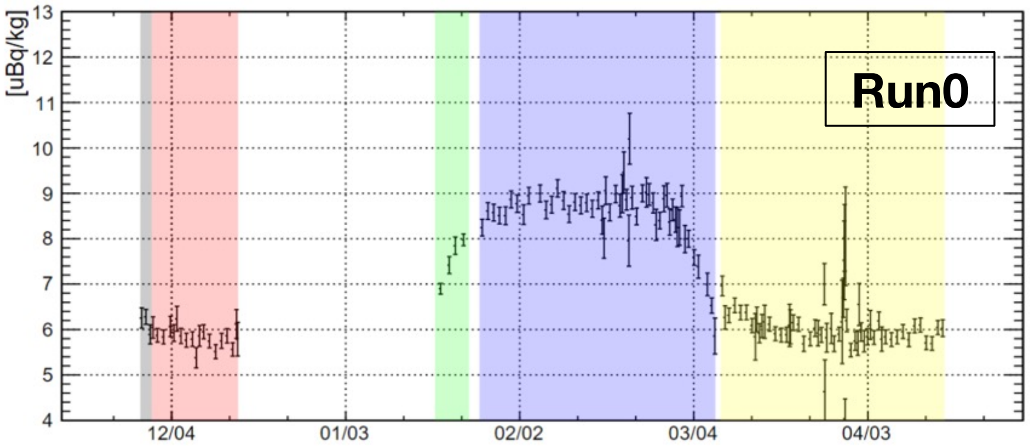
Main ER Backgrounds: ^{222}Rn

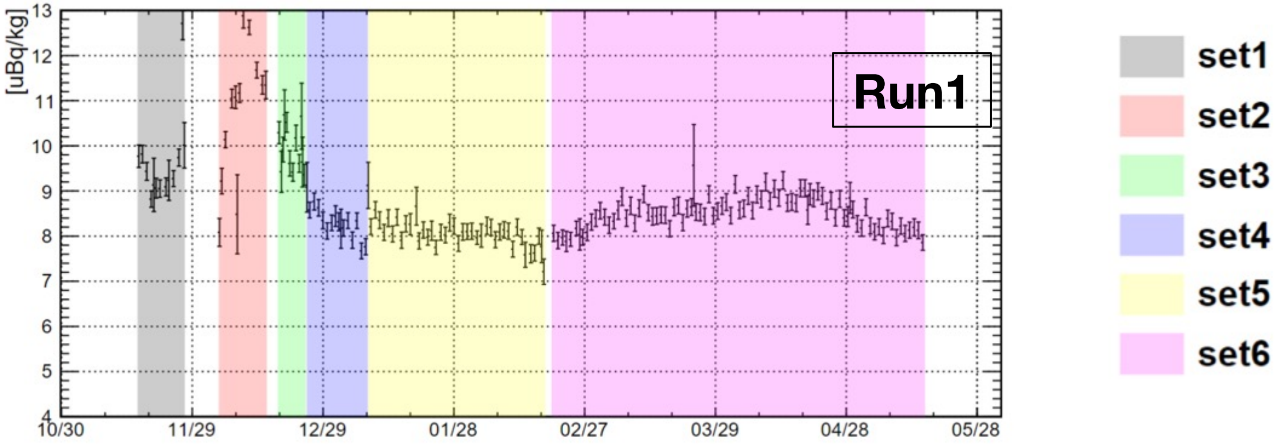
- **Rn level varies with running conditions**
- **Update the analysis**

Rn level	**μBq/kg**
Run 0	**7.07 ± 0.02(stat.) ± 0.23(sys.)**
Run 1	**8.67 ± 0.01(stat.) ± 0.27(sys.)**



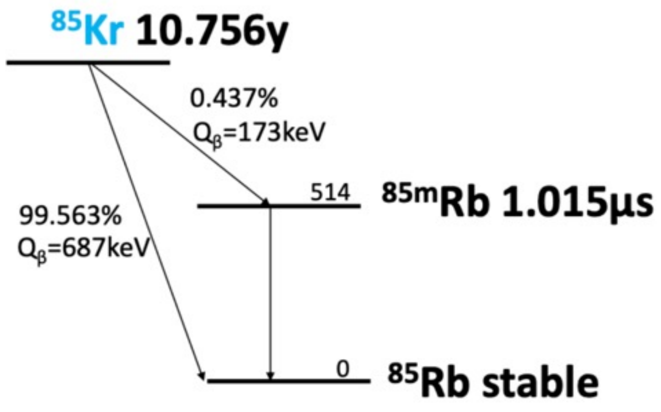
- **Circulation system to be upgraded**



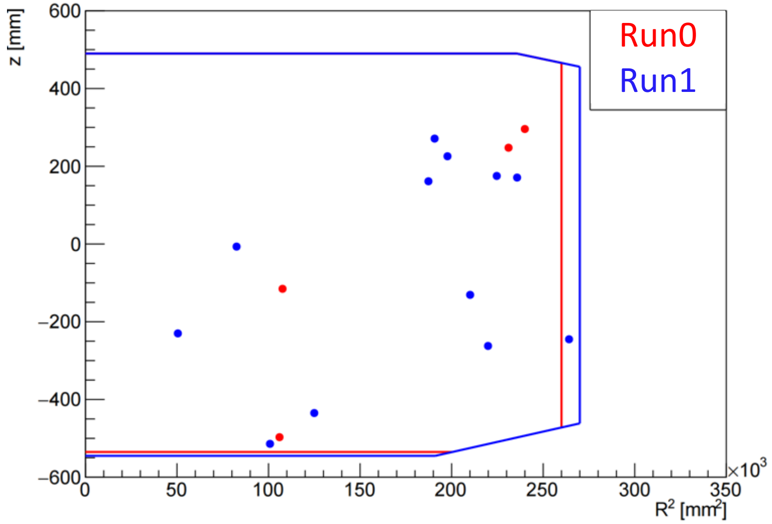


Main ER Backgrounds: ^{85}Kr

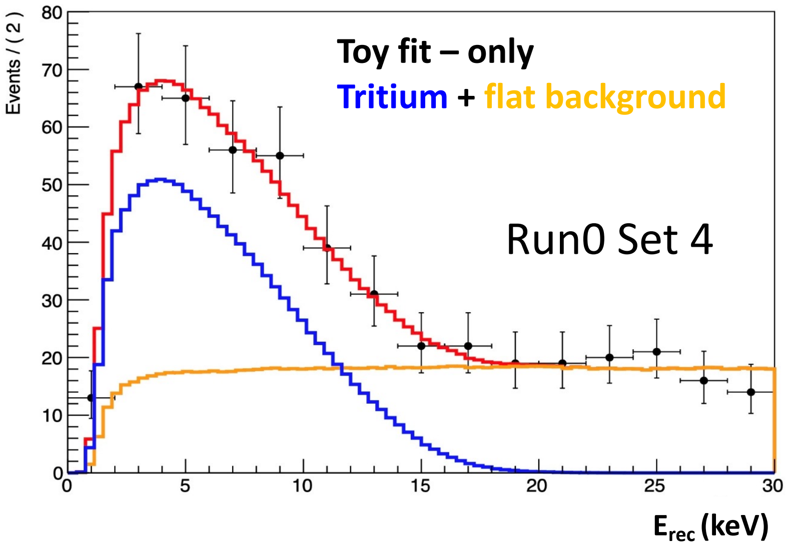
- **Compare to Commissioning run**
  - tightening beta-gamma coincidence selection
  - less contributions from accidental events

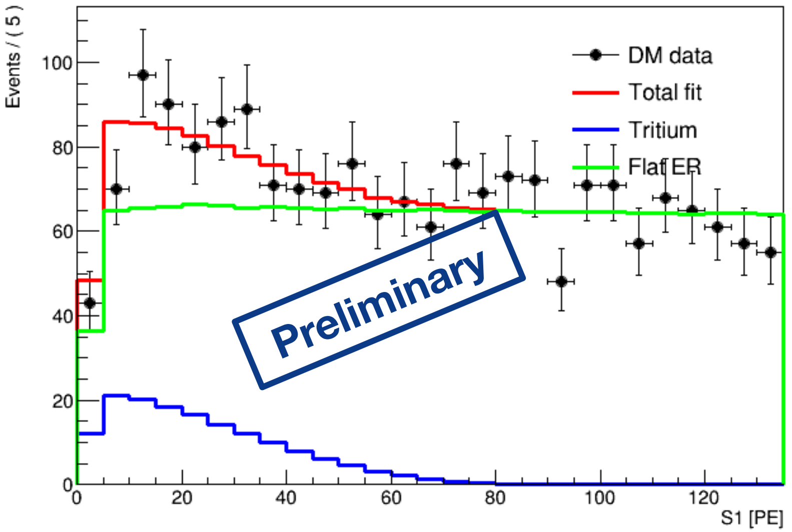


	β–γ events	accidental events	Kr/Xe [ppt (10^{-12})]
Run0 0.6 tonne-year	4	0.14 ± 0.04	**0.5 ± 0.3**
Run1 1.0 tonne-year	12	0.25 ± 0.05	**0.9 ± 0.3**



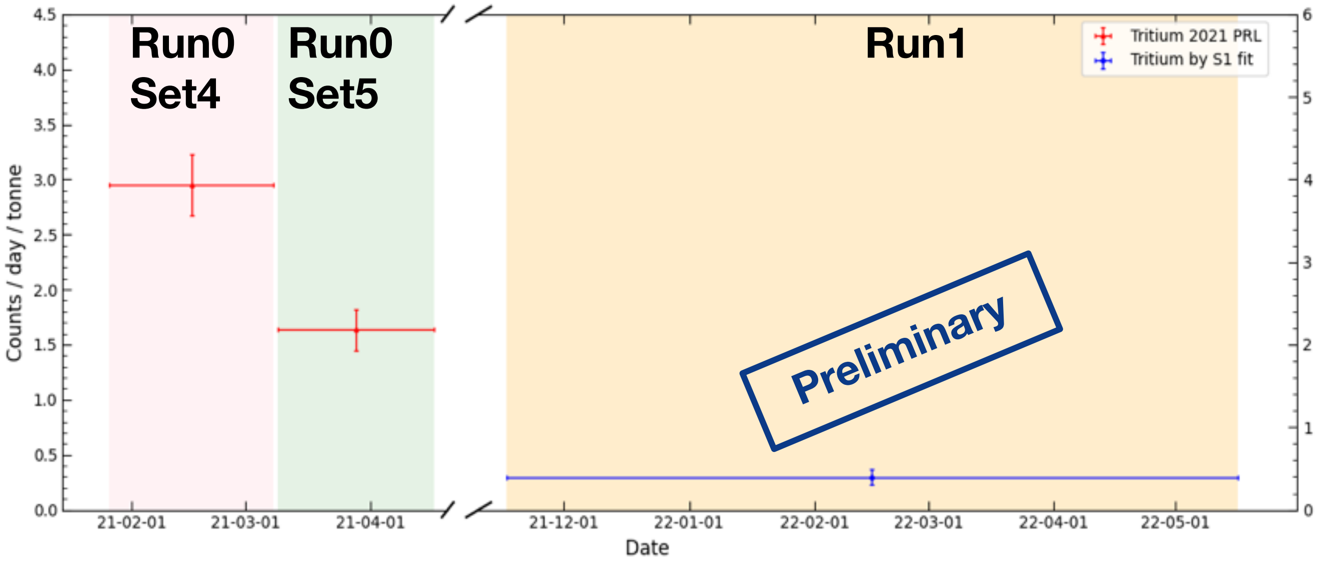
Main ER Backgrounds: Tritium



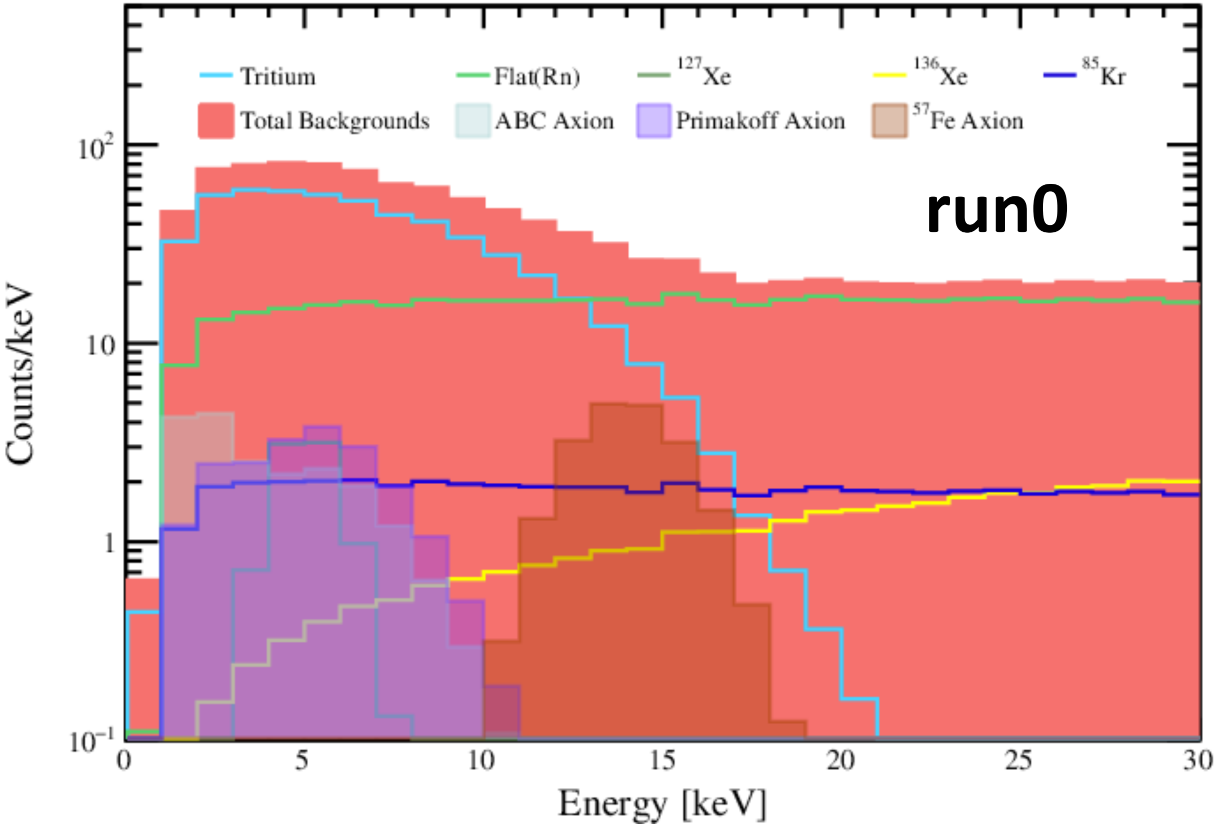


- Tritium spectrum identified in the data
- Likely originated from a tritium calibration at the end of PandaX-II;
- **Preliminary estimation of tritium level in Run 1:** fitting S1 spectrum, keeping S2 blinded

Tritium level	Run0 Set 4	Run0 Set 5	Run1
Counts/day/tonne	**3.0 ± 0.3**	**1.6 ± 0.2**	**0.4 ± 0.1**



Background Summary



Different from WIMP analysis, we extended the ROI to 30keV

- Rn emanation;
- Krypton contamination;
- Tritium;
- Radioactive isotopes of xenon: ^{127}Xe, ^{136}Xe, ^{124}Xe;
- Material: radioactivity of materials are assayed by HPGe;
- pp neutrino: theoretical estimation;
- others: surface, neutron, accidental, ^{8}B.

The combined analysis of run0 and run1 is under final check and the data is ready to unblind.

Summary and Outlook

- **PandX-4T has finished two physics runs;**
- **Combined analysis of Run0 and Run1 are updated;**
- **ER responses are calibrated with ^{220}Rn;**
- **Expected background contributions are estimated respectively; tritium level has significantly reduced in Run1;**
- **Exploring new physics with Run0 and Run1 data of PandaX-4T is ongoing!**

PandaX Collaboration

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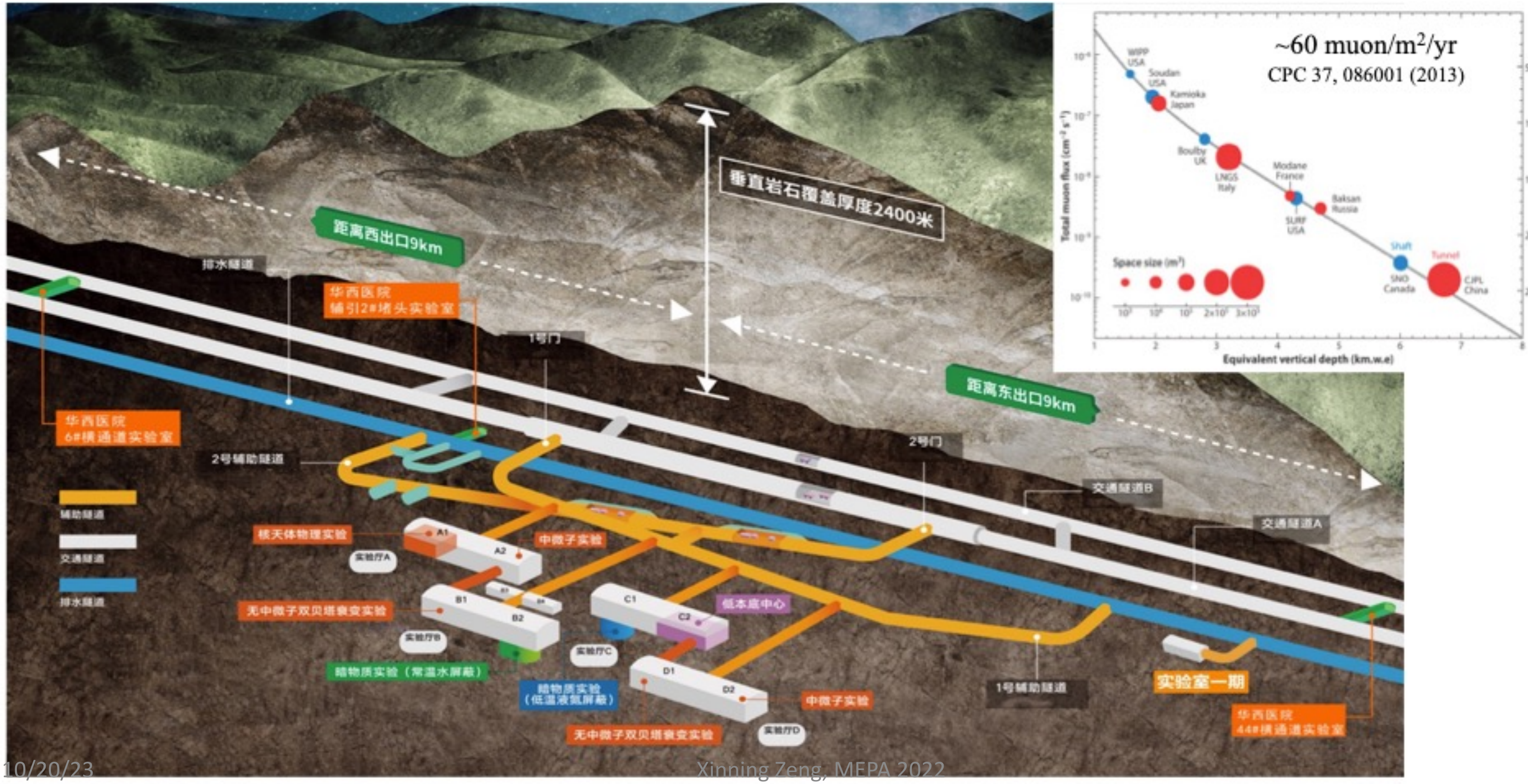
Backups

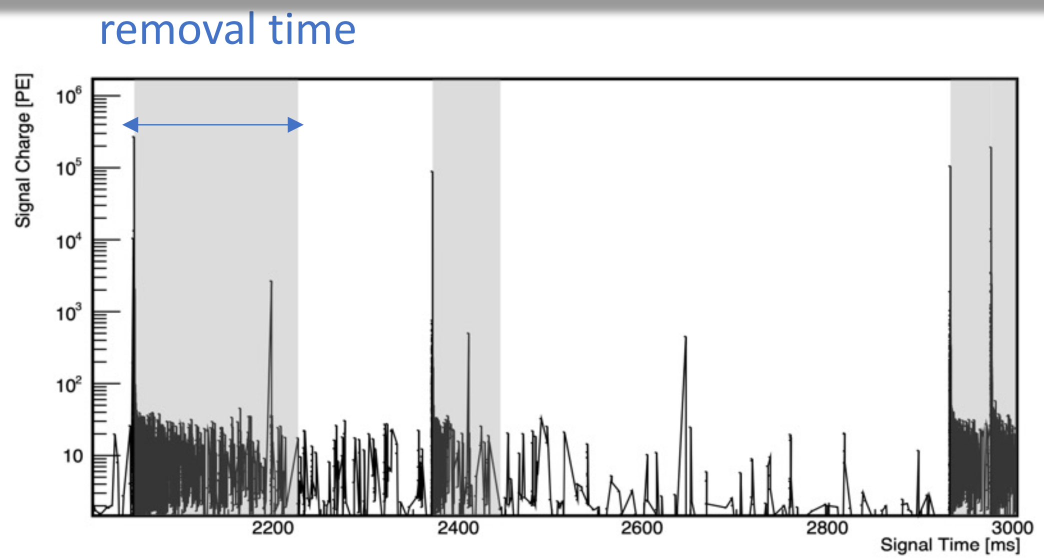
CJPL

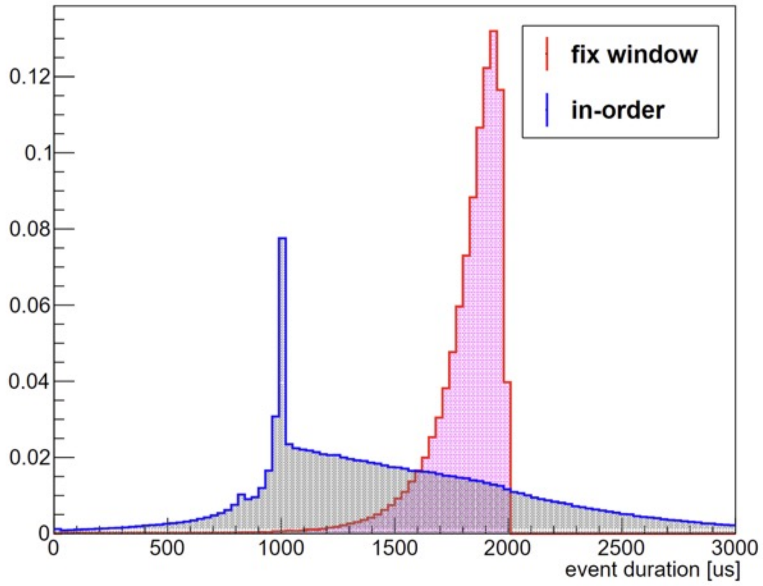


垂直岩石覆盖厚度2400米
距离西出口9km
距离东出口9km
排水隧道
华西医院
辅引2#堵头实验室
1号门
华西医院
6#横通道实验室
2号辅助隧道
2号门
交通隧道B
交通隧道A
辅助隧道
交通隧道
排水隧道
核天体物理实验
实验厅A
中微子实验
低本底中心
无中微子双贝塔衰变实验
实验厅B
实验厅C
暗物质实验（常温水屏蔽）
暗物质实验
（低温液氮屏蔽）
中微子实验
无中微子双贝塔衰变实验
实验厅D
1号辅助隧道
实验室一期
华西医院
44#横通道实验室
~60 muon/m^2/yr
CPC 37, 086001 (2013)
WIPP USA
Soudan USA
Kamioka Japan
Boulby UK
LNGS Italy
Modane France
SURF USA
Baksan Russia
Shaft
Tunnel
SNO Canada
CJPL China
Space size (m^3)
Total muon flux
Rock overburden (m)
Equivalent vertical depth (km.w.e)

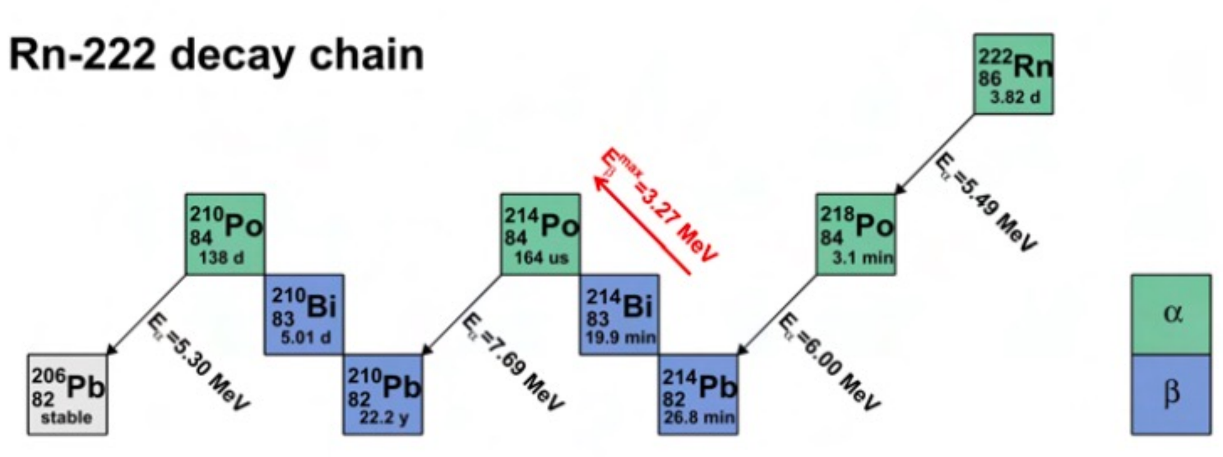
Combined Analysis of Run0 + Run1

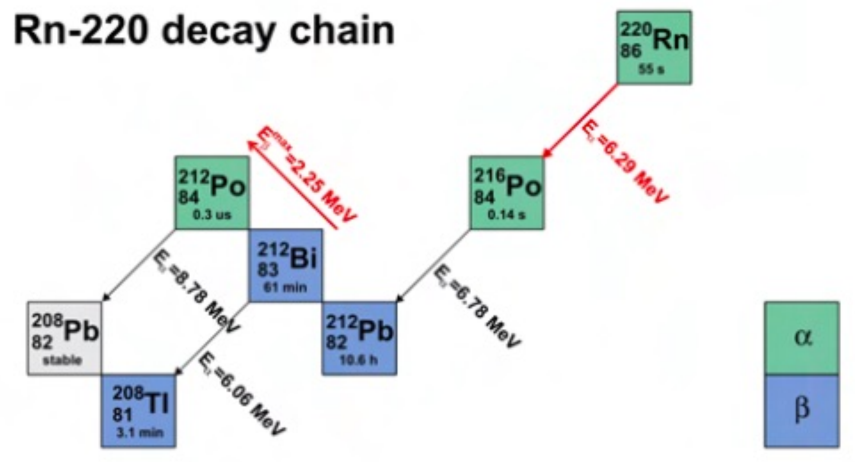
- ❑ **New active time determination**
  - window-size of removal time depending on the charge of large signal in front
- ❑ **New event window based on S2**
  - fix window: 1ms before and after
- ❑ **New event builder**
  - S1-S2 pairing requires quality of S1 in prior
- ❑ **New selection criteria**
  - charge-dependent cut threshold

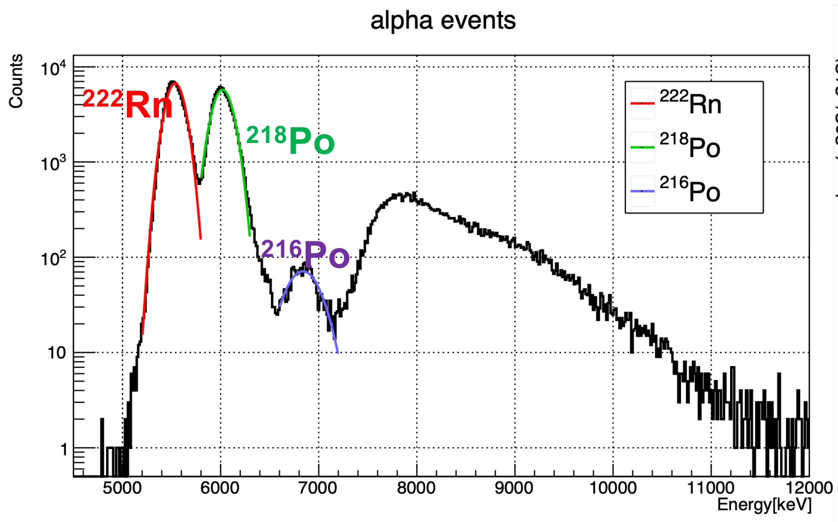


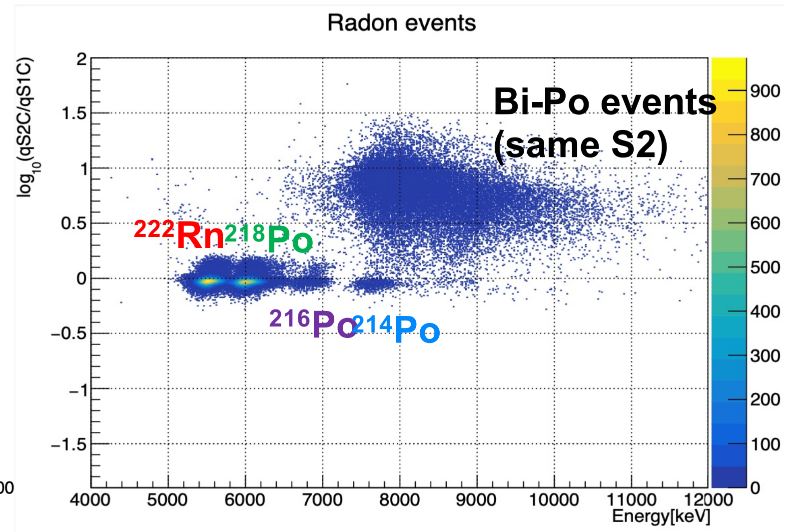


Main ER Backgrounds: Radon Emanation

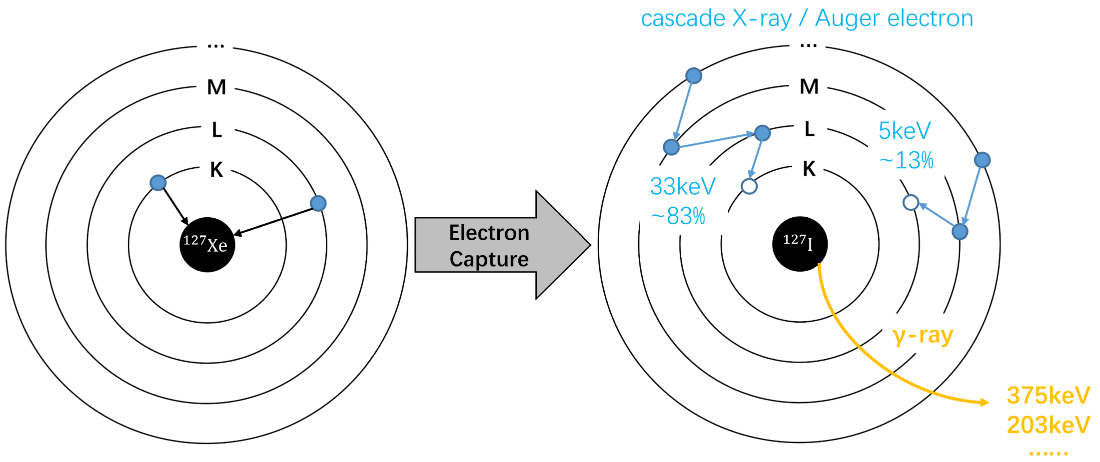


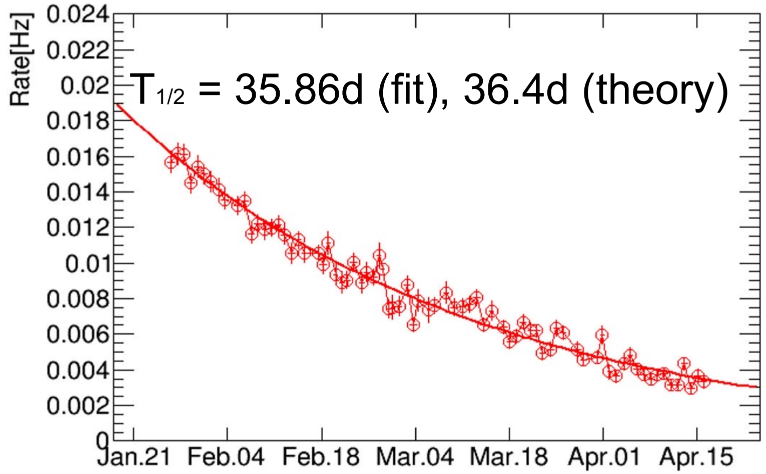


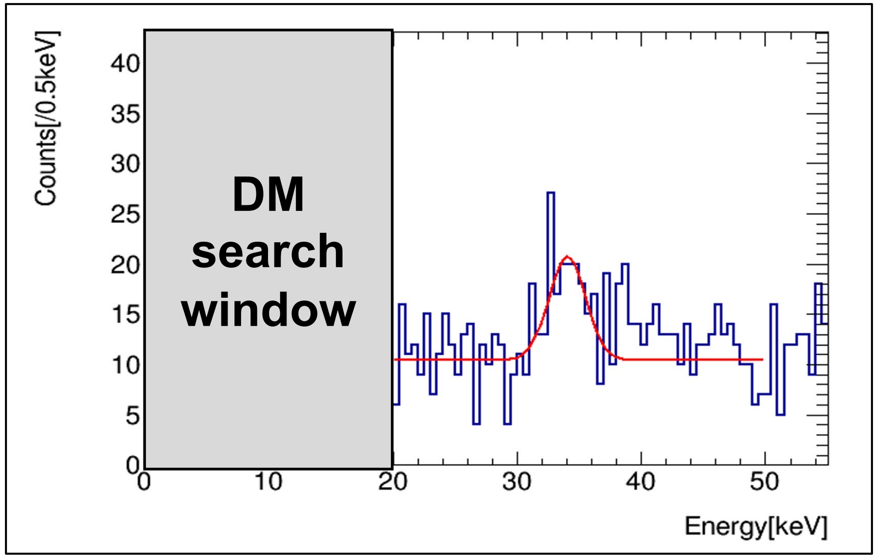




^{127}Xe (Cosmogenically Activated)

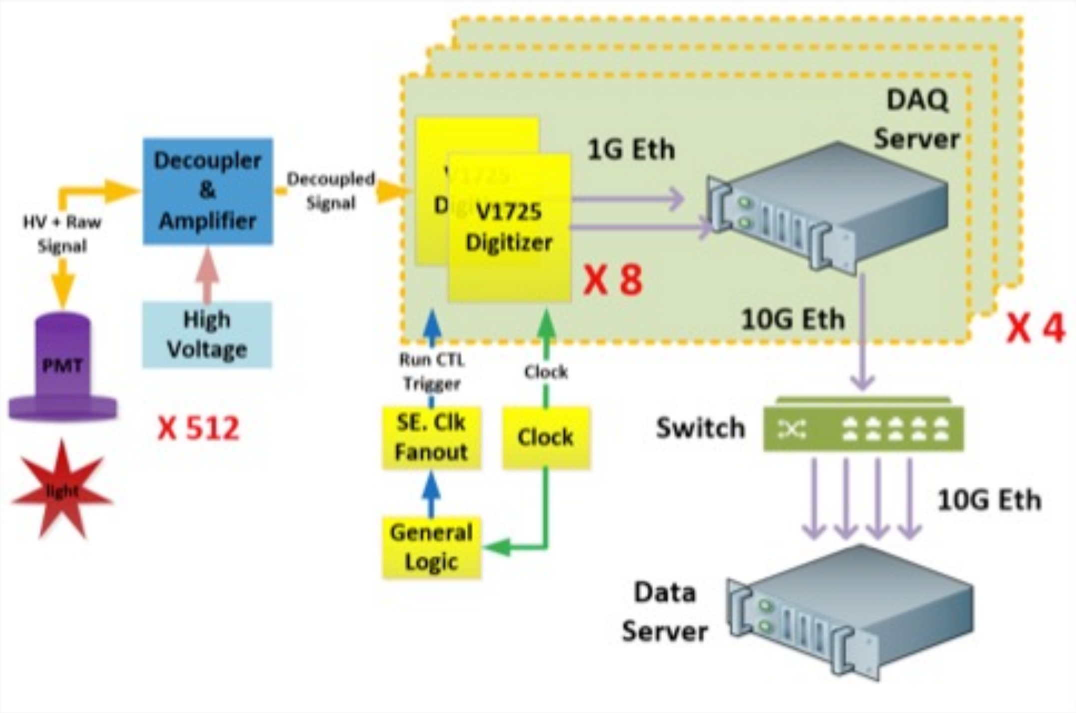




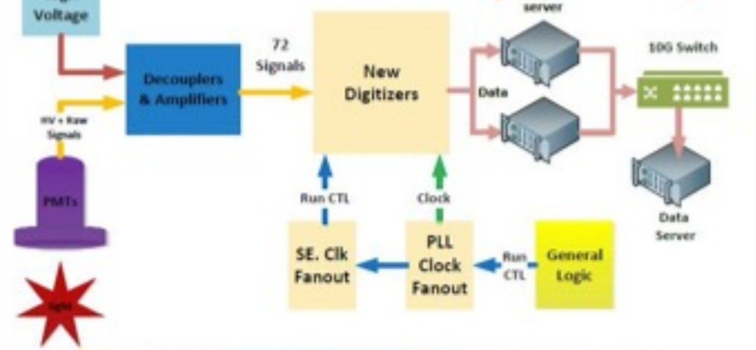


- **Expected background (5 keV): 8 ± 1 events**

Electronics



Custom-developed: 14-bit, 500MS/s



- V1725 Digitizer, 250 MS/s;
- Self-trigger mode: read out pulses above 20 ADC (~ 1/3 PE);

- Higher sampling rate;
- Accept out-trigger mode;